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Comparative analysis on waste to energy conversion chains using thermal-chemical processes

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Abstract

The paper presents the results of theoretical and experimental approach study on solid waste thermal-chemical treatment for power generation. Three main conversion processes were used: direct combustion, pyrolysis and gasification. When applied to large variety of wastes, the option for a certain treatment method (gasification especially due to process low stability) requires the knowledge of physical-chemical characteristics of the waste to be treated. Current debates on cost-effect of these young technologies compared to old incineration are mainly focused on biomass, especially wood under gasification conditions (using air). For atypical waste (MSW, industrial, food industry, farm) operation data or experimental results with respect to process global energy balance are not available for public or the information is restricted to general aspects. The experimental research focused on a large variety of heterogeneous waste (cellulose based, plastic, food industry, agriculture) to energy conversion efficiency. Based on experimental results the electrical power out-put was estimated for three main conversion chains using the mentioned processes.

Keywords: Waste-to-energy, pyrolysis, gasification, energy balance;

1. Introduction

Renewable surface fuels such as biomass and most types of waste are occurring in a widespread and diffuse way therefore de-centralized low and medium scale power units technologies are needed for their energy conversion. The low and medium scale power units present major disadvantages if common

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combustion process is used with respect to specific investment and global energy efficiency. Nevertheless large-scale use of combustion technologies for waste neutralization revealed a series of operation disadvantages in terms of global energy efficiency (high air excess) and polluting emissions (dioxins in the outgoing gases streams when chlorine based components are present in raw products). The high treatment temperatures and the massive presence of the oxygen facilitate the nitrogen toxic components and the flying ash transport (carrying the heavy metals, when present), imposing high efficiency and costly gases flue treatment utilities. Currently used technologies in chemical industry or power generation (using coal) such pyrolysis and gasification migrated to waste treatment sector within the last two decades as alternatives to combustion.

The pyrolysis technology can be used as pre-treatment stage both for combustion and gasification processes providing raw product physical-chemical transformation with combustibility properties improvement: homogeneity, superior low heating value [1]. The gasification process when conducted using steam presents undeniable advantages concerning the dioxins formation and low scale customized applications (distributed power generation). Based only on product low heating value the assessment of thermal treatment and power generation energy balance is not reliable due to complex product transformation during the pyrolysis and gasification stage. Current data bases on cost-effect of these young technologies compared to old incineration are mainly focused on biomass, especially wood under gasification conditions (using air). The research focused on a large variety of heterogeneous waste mixtures combustion, pyro-combustion and pyro-gasification with respect to global energy balance and power generation potential.

2. Experimental setup

2.1. Installation

For the combustion, pyrolysis and gasification process configuration a tubular electrically heated reactor and a calcination oven made by Nabertherm were used. The installations are modified according to experiment set-up within Laboratory of Renewable Energy Sources of Polytechnic University of Bucharest [2]. Laboratory scale tubular reactor consists of a refractory stainless steel tube, exterior electrically heated and with an interior diameter of 60 mm. Active heating area has a length of 750 mm. Horizontal tube furnace is equipped with two outlet tubes made for gas and liquid discharges resulted from treatments applied to solid masses. Two inlets are also present for treatment gas injection. The calcination oven is equipped with a precision balance being configured like a thermal balance for mass variation ratio as temperature function. The crucible capacity as in tubular reactor case is about 50 – 60 g. The configurations enable the precise control of process parameters: temperature, residence time, atmosphere, heating rate etc. [2].

The working temperature range for each installation is between 20°C to 1300°C. To ensure an inert/oxidant atmosphere in the installations during the thermal-chemical processes, nitrogen, steam or air was fed-in, the flow being controlled.

2.2. Products

The material used in this study is represented by a large category of heterogeneous solid waste: packaging waste, agriculture waste and food industry. The moisture content determined for the materials as arrived varied between 8% and 70%. Different analyses were performed on the dried products: proximate analysis, elemental analysis, high and low heating value determination. For the determination of volatile content the temperature was set at 800°C and the crucible with material previously graded,

stayed in the oven for 40 minutes. The samples obtained in the first stage are subjected to a combustion process in order to determinate the total content of the combustible materials, respectively the one of inert (non-combustible) fraction. The results are presented in Table 1.

Table 1. Proximate analysis of waste products

Product	Volatile [%]	Fix Carbon [%]	Inert [%]
Packaging waste	87.5	6.6	5.9
Food industry waste	91	7.5	1.5
Agriculture waste	74	21	5

The chemical composition of the materials was established using an elemental analyzer, with a sample weight which varied around 1 mg. The EA 3000 Series used analyzer uses the principle of dynamic flash combustion followed by gas chromatography separation of the resultant gaseous species (N_2, CO_2, H_2O, and SO_2) and TCD detection (Table 2).

Table 2. Elemental analysis of waste products

Product	C [%]	H [%]	N [%]	S [%]	Cl [%]	O [%]	A [%]
Packaging waste	36.8	5.1	0.1	0.2	0.1	35.4	5.9
Food industry waste	60.6	8.5	8.7	4.8	2.6	13.3	1.5
Agriculture waste	48.1	5.4	1.4	3.7	0	36.3	5

It can be concluded that the characteristics of these wastes are similar to different types of wood biomass when we refer in particular to volatile content and elemental composition.

The low heating value of products varies from 27 – 29 MJ/kg for package waste to 25 – 26 MJ/kg for food waste and 13 – 17 MJ/kg for agriculture waste (dry basis).

3. Results and discussion

3.1. Process run

Three main experiments were conducted on each waste type: combustion, pyrolysis and steam gasification. The processes were conducted in the tubular batch reactor, each product sample being exposed to a specific temperature in the preheated furnace, hence subjected to a flash process similar to industrial operating conditions.

The mass of each sample varied between 50 and 60 grams depending on products specific weight. In this case the mass was considered quasi-constant and in a significantly small quantity suited for the crucible. Nevertheless the conditions encountered in an industrial process are different from experimental

size units, such as the one in case, because heat and mass transport mechanisms will influence the process by-products fraction rate and properties, but the variation tendencies remain the same.

For the combustion process the excess air was 1.3 – 1.7 and the temperature 900°C - 1200°C. For the pyrolysis experiment the flow of nitrogen into the reactor was 100 cm^3/min and the heating rate approximately 40 – 50 °/min. The range of temperature varied between 350°C and 550°C. For the gasification experiment, the steam / carbon ratio was about 1.2 – 1.3 and the temperature range 850°C - 1050°C [3].

3.2. Results – energy balance

For all products the maximum yield of tar is found at temperatures between 500°C and 550°C, after this temperature it is observed a decrease of the compound. In addition, the solid char yield decreases with increasing pyrolysis temperature, the maximum being achieved at 350ºC – 450ºC. An optimum valorization of these derived products requires the maximum energy potential of the by-products for the minimum energy consumption during the pyrolysis stage treatment. The specific energy content of the pyrolysis by-products varied 13 MJ/kg – 20 MJ/kg for tar, 23MJ/kg – 26MJ/kg for char and about 7 MJ/kg for pyrolysis gas depending on product type an pyrolysis operating parameters [4], [5], [6], [7].

To estimate the energy consumption for pyrolysis and gasification processes the drying, devolatilization and gasification sequences were calculated separately based on experimental data. A series of simplifying assumptions were made with respect to equipment efficiencies. The calculations are theoretical for an overall perspective on product energetic valorization. The feed-in flow of raw waste was considered equal to 1 kg/s.

Drying sequence

The heat required for the complete water vaporization is given by the equation below, where T_s represents the inlet fuel temperature and T_f the temperature at the end of the drying stage:

$$Q_{vap} = m_{raw\ fuel} * w_{humidity} \left[\lambda_v (373\,K) + \int_{T_i}^{373\,K} c_{water}^{liq}\, dT + \int_{373\,K}^{T_f} c_{water}^{vap}\, dT \right] \text{[kJ]} \quad (1)$$

where: $m_{raw\ fuel}$ – mass of raw product [kg]; $w_{humidity}$ – water content [%]; λ_v – vaporization heat [kJ/kg]; c – specific heat [kJ/kgK-1].

It was assumed that water vaporization is practically completed in the range 160-190°C even if for product organic compounds above 105ºC the liberation of volatiles occurs but at low rate.

$$Q_{fuel}^{dry} = m_{fuel}^{dry} \int_{T_s}^{463\,K} c_{p\_fuel\,dry}\, dT \ \text{[kJ]} \quad (2)$$

where: m_{fuel}^{dry} - mass of dried product [kg]; $c_{p\_fuel\,dry}$ - specific heat of dried product [kJ/kgK-1].

The heat absorbed by the raw surface fuel to reach the 190°C is:

$$Q_{drying} = Q_{fuel\,dry} + Q_{vap} \quad (3)$$

Devolatilization sequence

The heat required for 1 kg of waste (fuel) to liberate the complete amount of volatiles is given by:

$$Q_{pyr}=m_{rawfuel}*(1-w_{humikdity})*E_a+m_{carbon}*c_{p\_carbone}*(T_{pyr}-T_f)+m_{inert}*c_{p\_inert}*(T_{pyr}-T_f) \quad (4)$$

where: E_a - activation energy [kJ/kg]; m_{carbon} - mass of fixed carbon in the char [kg]; m_{inert} - mass of inert fraction in the char [kg]; T_{pyr} - pyrolysis temperature [K]; T_f - drying stage temperature [K].

Where E_a represents the activation energy for the pyrolysis process and is function of fuel type and heating rate (technology).

Steam - Gasification sequence

The heat required for 1 kg of char from pyrolysis stage to be completely converted to syngas is:

$$Q_{gasif} = m_{carbon} * E_a + (m_{carbon} * c_{p\_carbon} + m_{inert} * c_{p\_inert}) * (T_{gas} - T_{inlet}) \text{ kJ/kg}_{\text{char}} \quad (5)$$

where: E_a - activation energy [kJ/kg]; m_{carbon} - mass of fixed carbon in the char [kg]; m_{inert} - mass of inert fraction in the char [kg]; T_{gas} - gasification process temperature [K]; T_{inlet} - char feed-in temperature [K].

For the steam gasification process the energy required for steam production, including the vaporization and superheating from saturation temperature to gasification temperature, is given by:

$$Q_{vap} = m_{water} * [\lambda_v(373\,K) + \int_{T_i}^{373K} c_{p\_water}^{liq} dT + \int_{373K}^{T_{gas}} c_{p\_water}^{vap} dT] \text{ [kJ]} \quad (6)$$

where: m_{water} – mass of water for steam generation [kg]; λ_v – water vaporization heat [kJ/kg]; c_{p_water} – water specific heat liquid and gaseous phase [kJ/kgK-1]; T_i – water feed-in temperature (15°C); T_{gas} – gasification temperature (850°C - 1100°C).

A series of assumption were made for the energy conversion chain, based on: raw products and pyrolysis by-products; primary source conversion stage process (combustion efficiency, pyrolysis and gasification energy demand); thermodynamic cycle efficiency. These assumptions are based on experimental data and industrial equipments characteristics:

- Combustion stage: grate or pulverized combustor. Excess air: 1.35 – 1.7.
- Pyrolysis stage: rotary kiln, externally heated. Nitrogen injection at start-up (gas exhaust from thermal engine can be used).
- Gasification: rotary kiln externally heated / down draft. Steam injection.
- Thermodynamic cycle: steam turbine or internal combustion engine Diesel-Gas.
- Energy efficiency: is characteristic to equipment depending on power range. The pyrolysis stage is directly connected to gasification one. The sensitive heat of pyrolysis by-products enters the gasification unit in proportion of 80% – 90%. The heat flow from engine technological cooling together with the sensitive heat of exhaust gases is used in pyrolysis stage.
- Pyrolysis by-products: the gas and 0.3 – 0.6 of tar production is used for pyrolysis heat supply. The char and 0.4 – 0.7 of tar production is used in gasification stage.
- The water vapors liberated in pyrolysis stage is used in gasification stage.

First large category of cellulose-based products is represented by agriculture waste with medium-high water content and average-low heating value (dry basis). Figure 1 presents the estimation of electric power out-put for agriculture waste as function of raw product humidity. Usually the humidity of waste generated in this activity sector varies from 25% - 60%. Due to its non-dangerous class the product can be first submitted to natural our forced convective drying in open space or dedicated storehouses. This procedure can decrease the water content down to 35%. No additional advanced thermal drying is required. For this type of waste the direct combustion represents the simplest and the most energy effective solution. The maximum power that can be recovered varies from 2.2 MWe to 3.7 MWe depending on product water content. The pyro-combustion provides 1.4 MWe up to 2.35 MWe. This solution can be used only for agriculture waste produced discontinuously in large quantities that cannot be stored for long period of time.

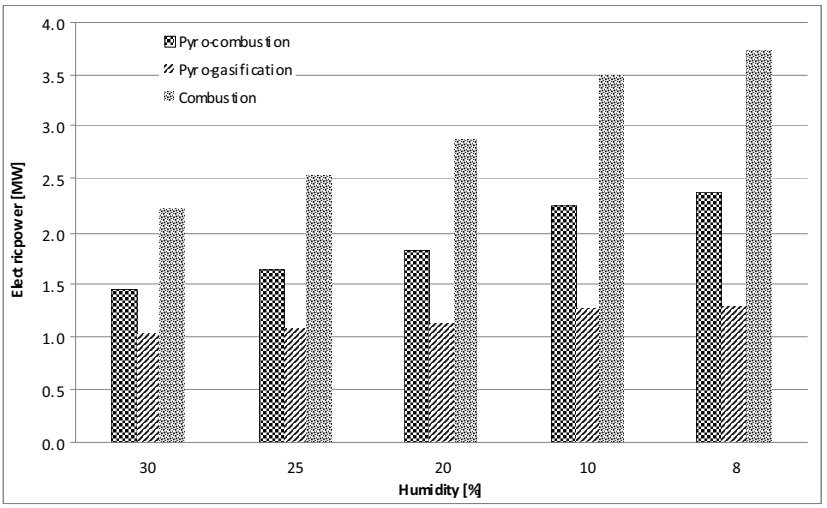

Fig. 1. Power generation from agriculture waste using thermal-chemical conversion processes

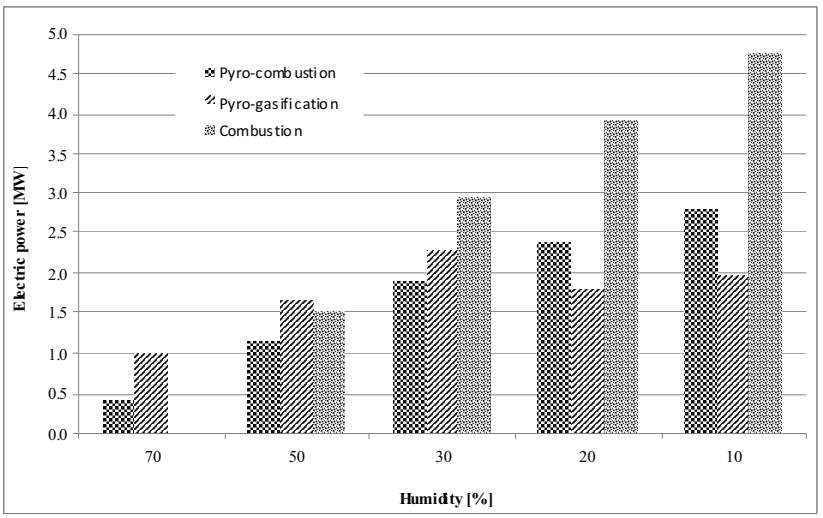

Fig. 2. Power generation from food industry waste using thermal-chemical conversion processes

To avoid the investment in high capacity power plant that operates for a short period of time the pyrolysis stage can be used for product stabilization and combustibility properties improvement. The by-products can be stored providing a continuous feed-in flow for a smaller power plant unit operated permanently [8]. The pyro-steam-gasification for this type of product is limited to about 1 MW_e and can be sustained only by lower investment, operation and maintenance costs. Nevertheless for this type of product the combustion-steam cycle represents the first option for energy recovery. Depending on site particularities the pyro-combustion can be successfully used.

Another category of waste is represented by high heating value products (dry basis) not suitable for energy generation due to high water content that cannot be decrease through low energy consumption methods. This limitation is introduced by the potential dangerous class of the product if stored for short-medium term. In this case the neutralization of the product is required, usually by thermal treatment. The results of power generation estimation based on experimental data are presented in Figure 2. At 70% water content the self-sustained combustion is impossible and, even at 55% humidity support fuel is required. As presented above the product used for this analysis has 24 MJ/kg low heating value (dry basis). This potential is decreased to about 6.5 MJ/kg at 70% humidity. Even if there are coals in this specific energy content currently used for power generation the presence of water and the product consistency make it unusable for combustion.

For this case the pyro-steam-gasification process coupled with thermal engine could represent the viable solution for the humidity range between 70% and 50% (the real case situation). The electric out-put that can be generated is about 1MW_e – 1.65 MW_e. The plant is operated only on syngas. The support fuel is required only for start-up and engine power adjustment. We noticed that the maximum power out-put is reached at 30% humidity of the product. If the humidity of the product decreases under this value the net electric power diminish due to energy consumption for steam generation.

The water vapor liberated in pyrolysis stage is used in gasification stage therefore the water vaporization heat consumed in pyrolysis stage is recovered in gasification one. If product water content does not exceed 45% the direct combustion still remains the best solution. As in previous case the pyro-combustion can present an alternative if waste generation is discontinuous. As in combustion case the maximum energy recovery is reached for the minimum water content. In this analysis a large series of variables were considered such as: fixed carbon / inert fraction ratio in the char, water content of the tar, char structure, pyrolysis and gasification activation energy. Research is progress. For the heterogeneous solid waste with high energy content (over 22 MJ/kg) and low water content (under 45%) the best energy efficient solution is the direct combustion. Nevertheless the waste source particularities together with product thermal-physical-chemical properties, risk pollutants content and investment cost can shift the economic efficiency of the solution.

4. Conclusions

The paper presents the results of comparative analysis of waste to energy conversion chains using combustion, pyro-combustion and pyro-gasification applied to three different categories of heterogeneous solid waste. Experimental results from pyrolysis and gasification processing of waste were used in the assessment. The research focused on products physical-chemical properties quantification by experimental approach: primary analysis and elemental analysis. Low temperature pyrolysis conducted at 350ºC – 550ºC and high temperature steam gasification at 850ºC – 1050ºC were used The pyrolysis experiments revealed that minimum treatment period required for complete carbonization of waste is between 30 and 45 minutes. Based on experimental results and industrial operation units characteristics

the electric power generation was estimated together with implementing solutions for energy recovery. For products with water content over 45% but also high calorific value (dry basis) the first option could be the pyro-vapor-gasification combined with Diesel-gas engines. If product water content does not exceed 45% the direct combustion still remains the best solution. The pyro-combustion can present an alternative solution if waste generation is discontinuous.

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